Biomechanics of the Optic Nerve Sheath in VIIP Syndrome

C. Ross Ethier[1], Julia Raykin[1], Rudy Gleason[1], Lealem Mulugeta[3], Jerry Myers[2], Emily Nelson[2], Brian C. Samuels[4]

[1]Department of Biomedical Engineering, Georgia Institute of Technology/Emory University, Atlanta, GA; [2]NASA Glenn Research Center, Cleveland, OH; [3]Universities Space Research Association, Houston, TX; [4]Department of Ophthalmology, U. Alabama at Birmingham, Birmingham, AL

Georgia Tech

Wallace H. Coulter Department of Biomedical Engineering at Georgia Tech and Emory University

EMORY UNIVERSITY

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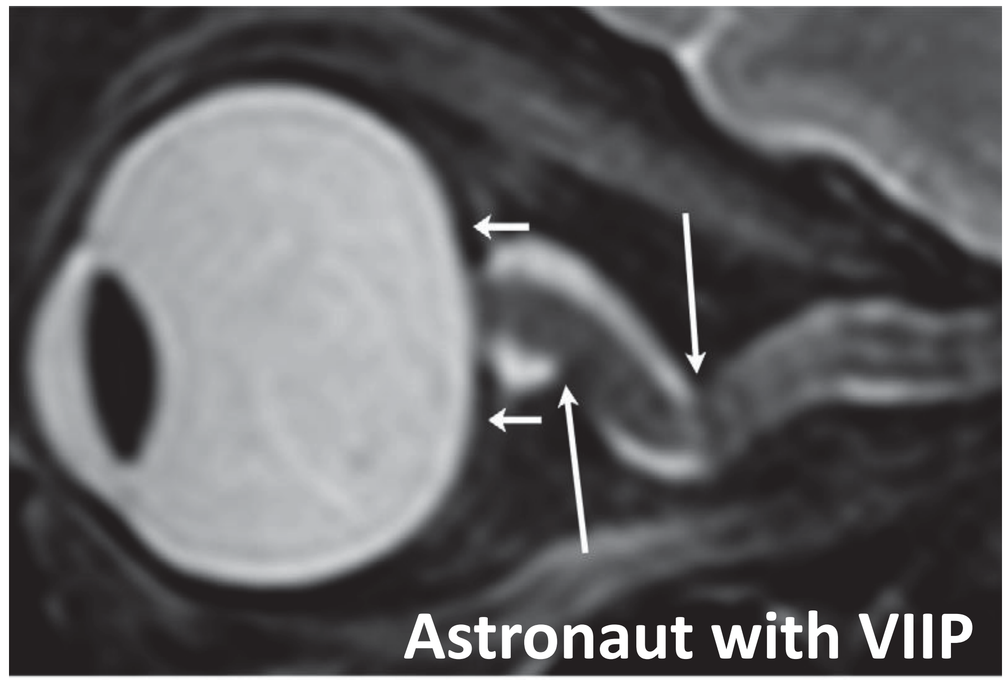
Visual Impairment and Intracranial Pressure (VIIP) Syndrome

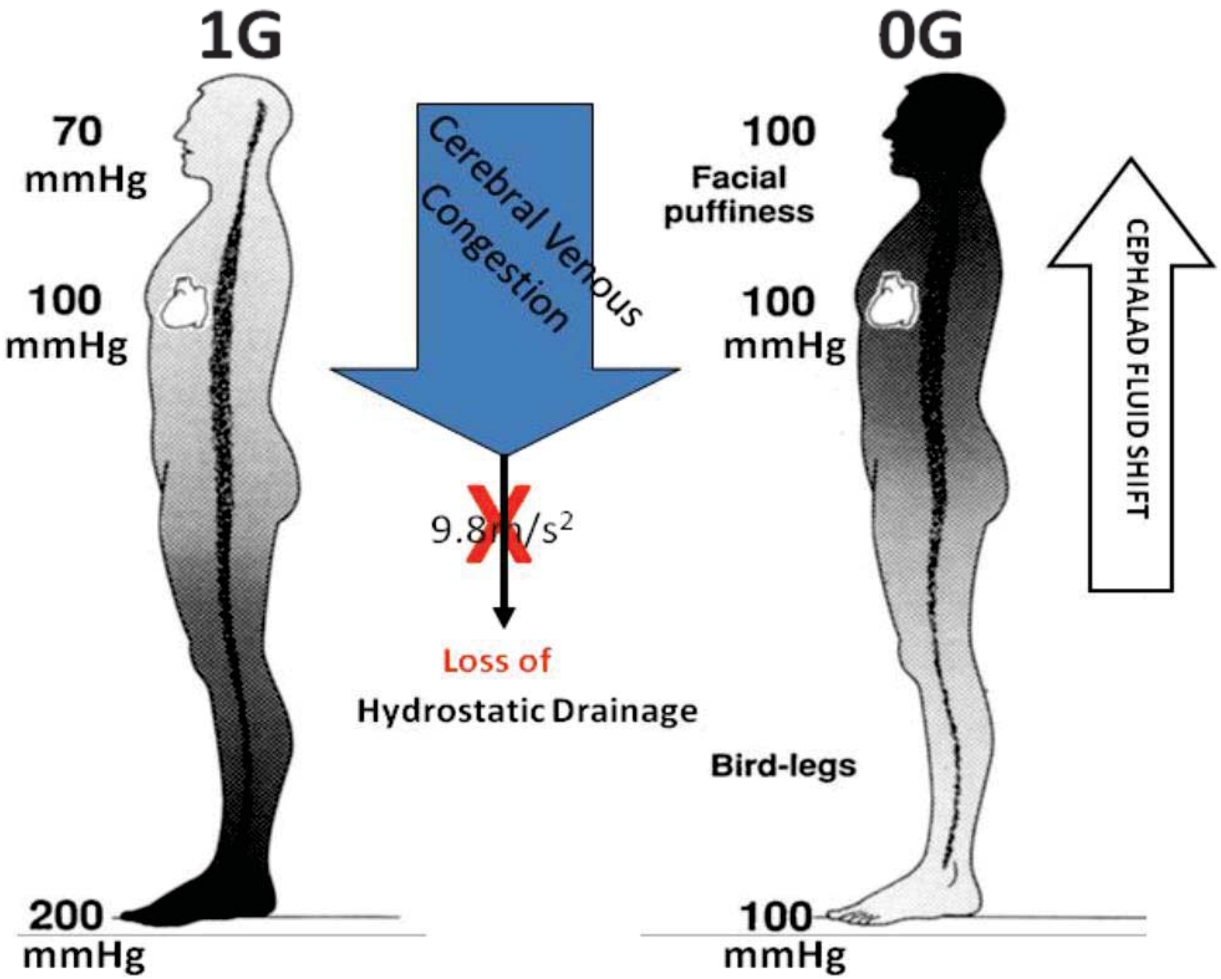
- Permanent changes in visual function after long-duration space flights
  - 41.7% incidence in U.S. astronauts

Structural Changes in the Optic Nerve



Kramer et al. Radiology, 2012.

Cephalad Fluid Shifts



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Hypothesis

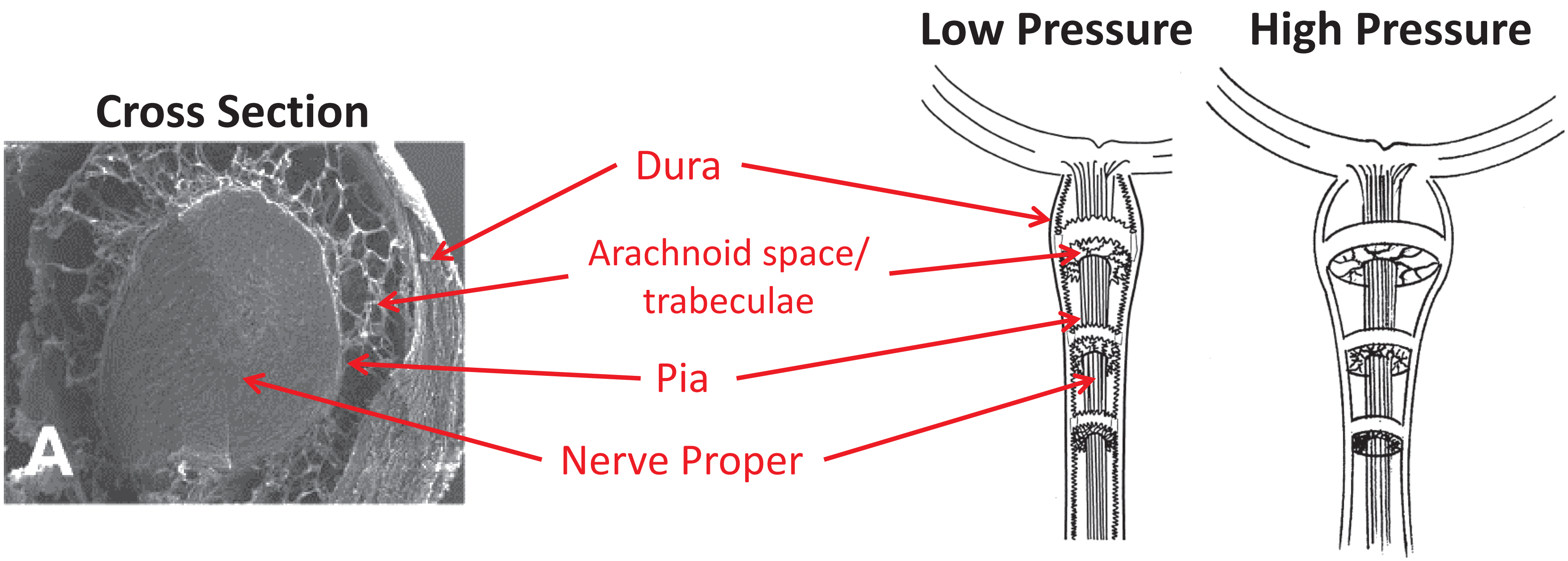
Increased CSF pressure drives remodeling of the posterior eye and the optic nerve sheath

Goal

Study the biomechanical response of the optic nerve sheath and posterior eye to elevated CSF pressures

- Eventually, understand visual disturbances that occur during long-duration space travel

Optic Nerve Sheath: Anatomy

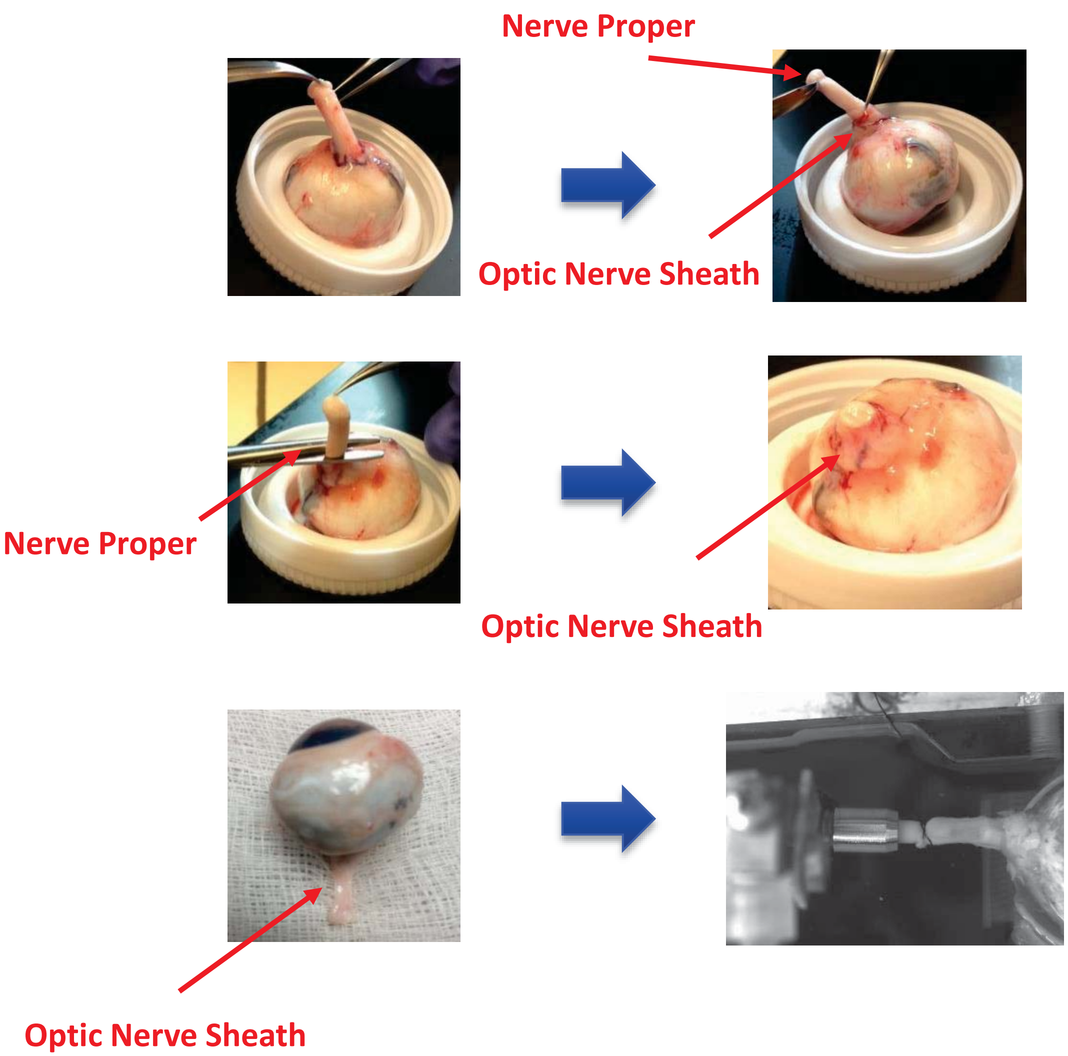


Killer et al. Brain, 2006.

Hansen et al. Acta Ophthalmologica, 2011.

EXPERIMENTS

Experimental Protocol: Inflation Test

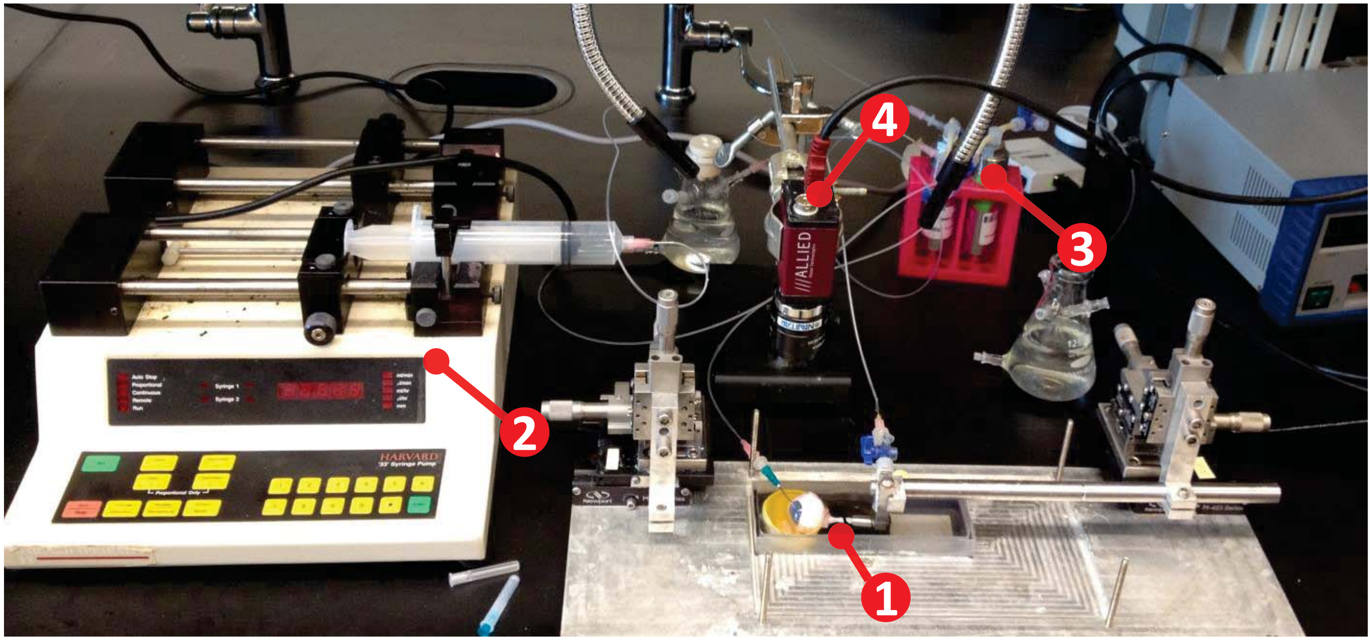


1. Sheath is peeled away from the nerve proper

2. Nerve proper is cut away

3. The optic nerve sheath is cannulated and connected to a pressure control system

Experimental System



System Components:

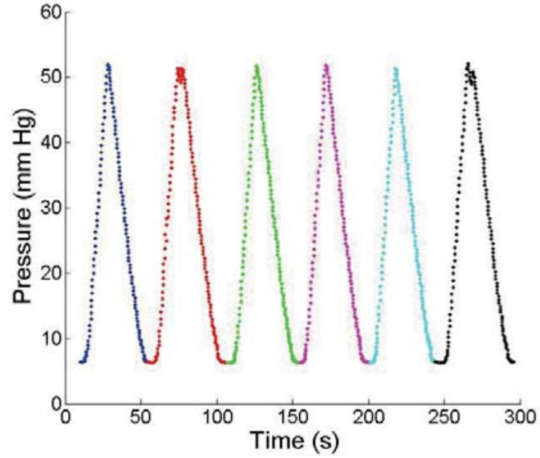
1 - Specimen bath/mounted porcine eye

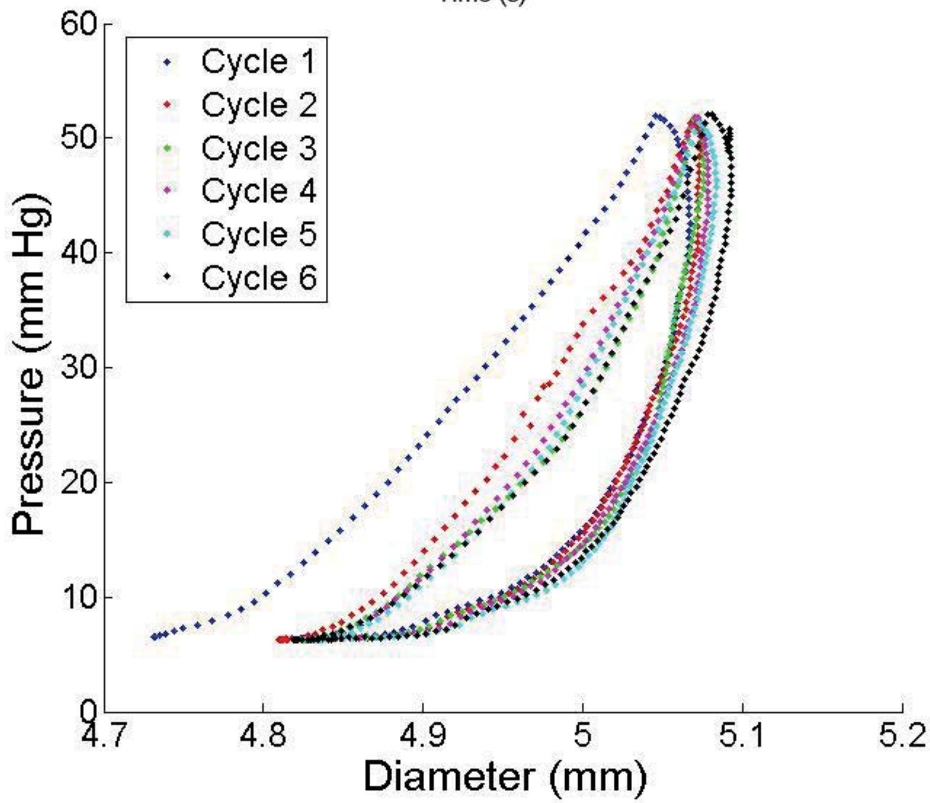
2 - Syringe pump

3 - Pressure transducers

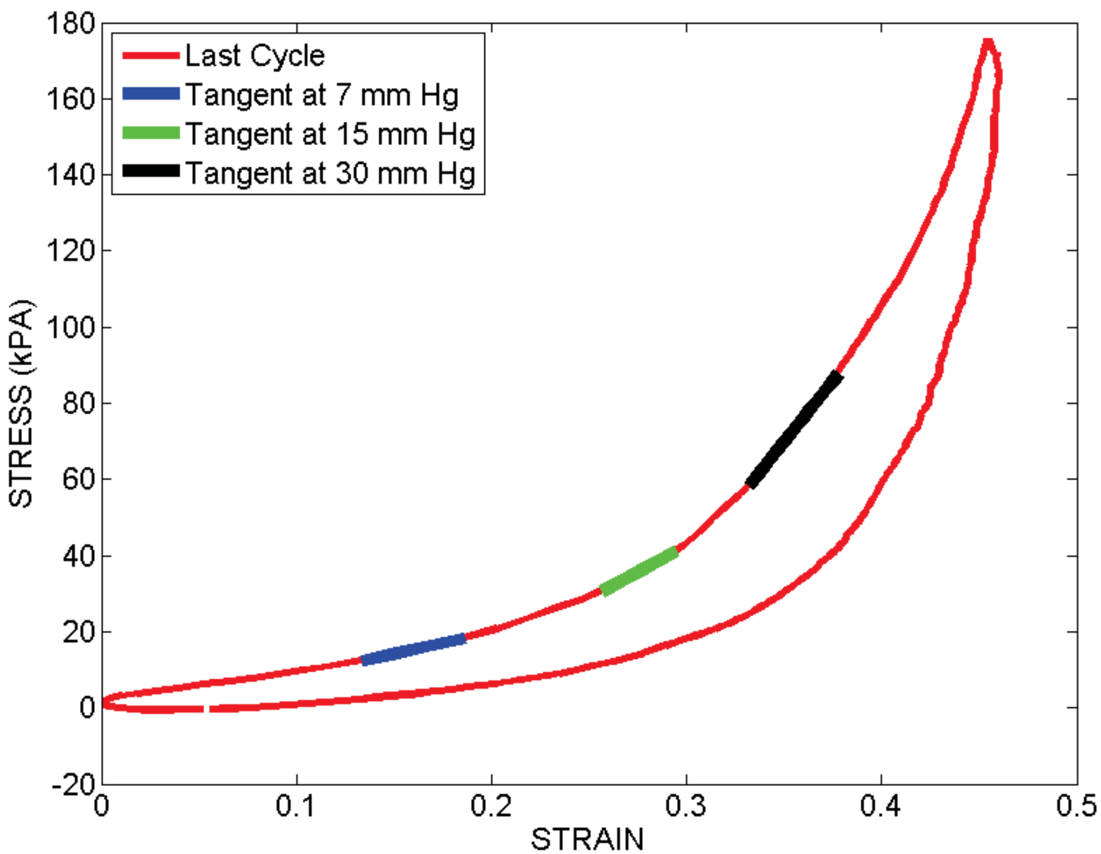
4 - CCD camera

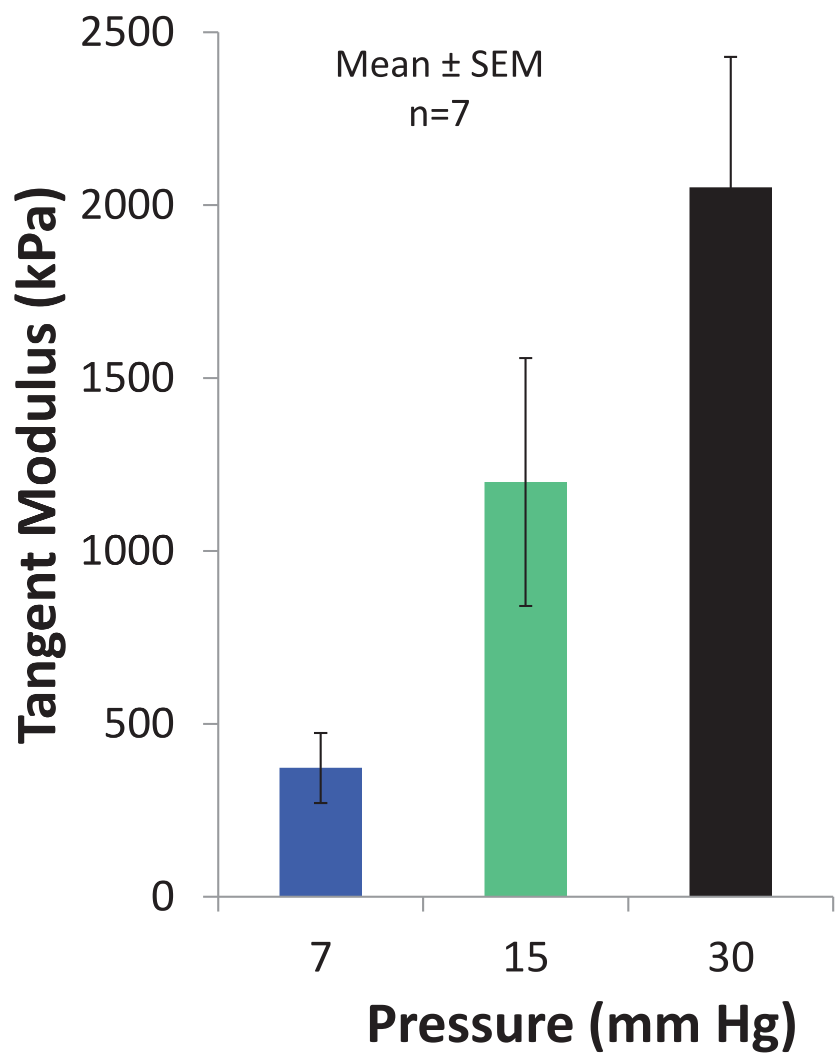
Pressure-Diameter Tests





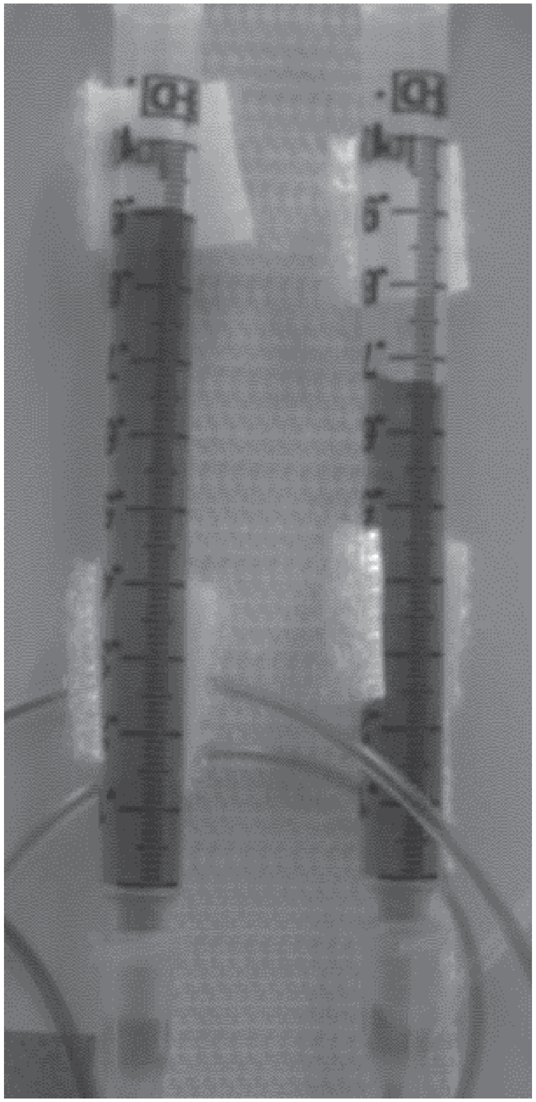
Modulus Increases at Higher Pressures

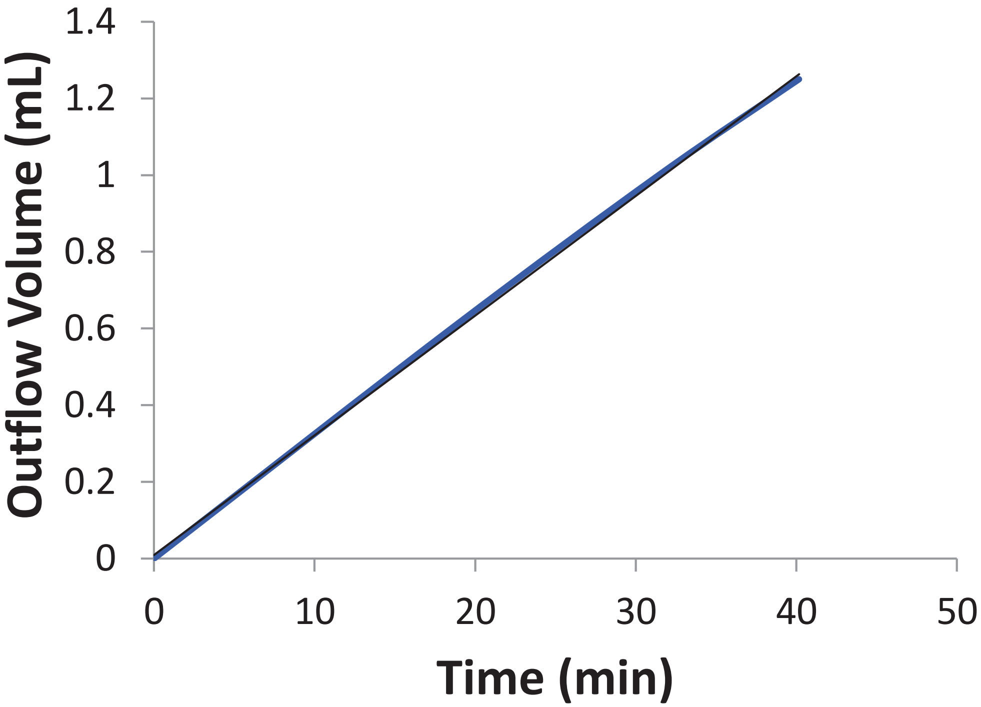




$$\varepsilon = \frac{r}{r_o} - 1 \qquad \sigma = \frac{Pr}{h}$$

Permeability - Experimental Setup





Permeability - Results

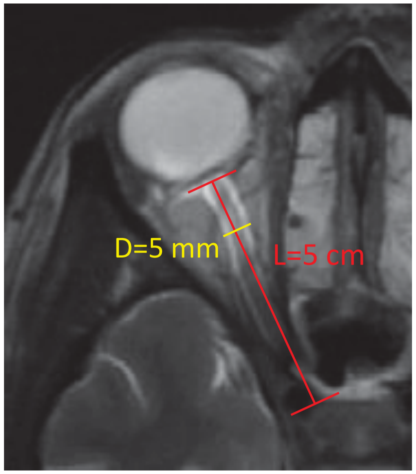
Permeability ($\mu L/min/cm^2/mm\ Hg$)
0.79 ± 0.12 (mean ± SEM; n=17)

Implication for Humans:

$Outflow\ Rate = K \cdot P \cdot A = 125 \frac{mL}{day}$ at 7 mm Hg

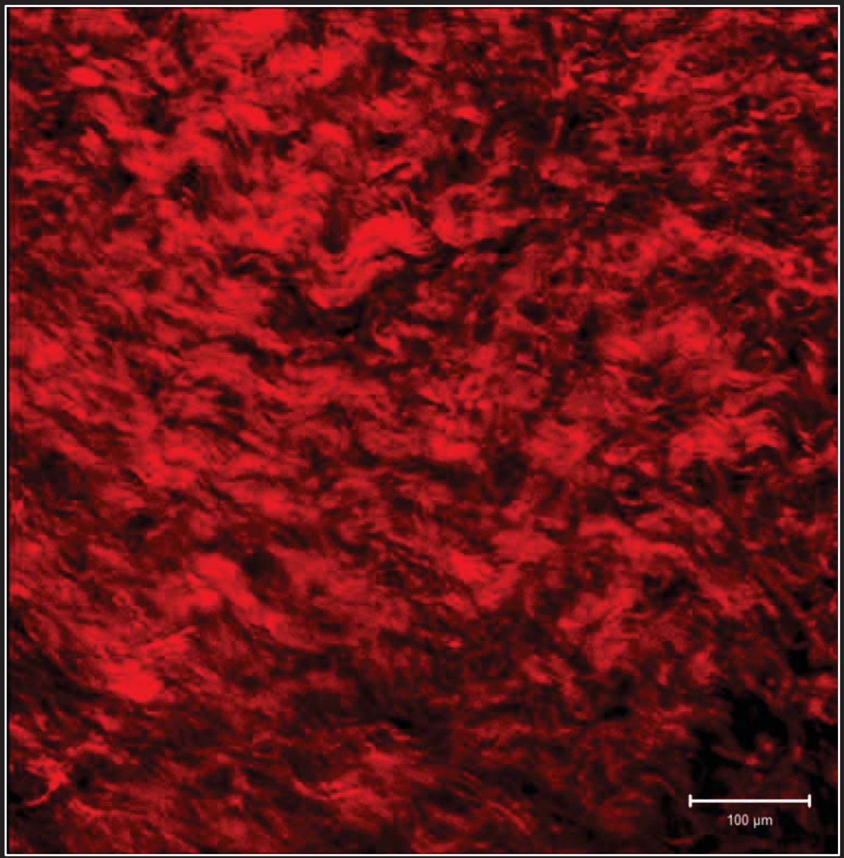
20% of daily CSF production

$A = 2 \cdot (\pi D L)$

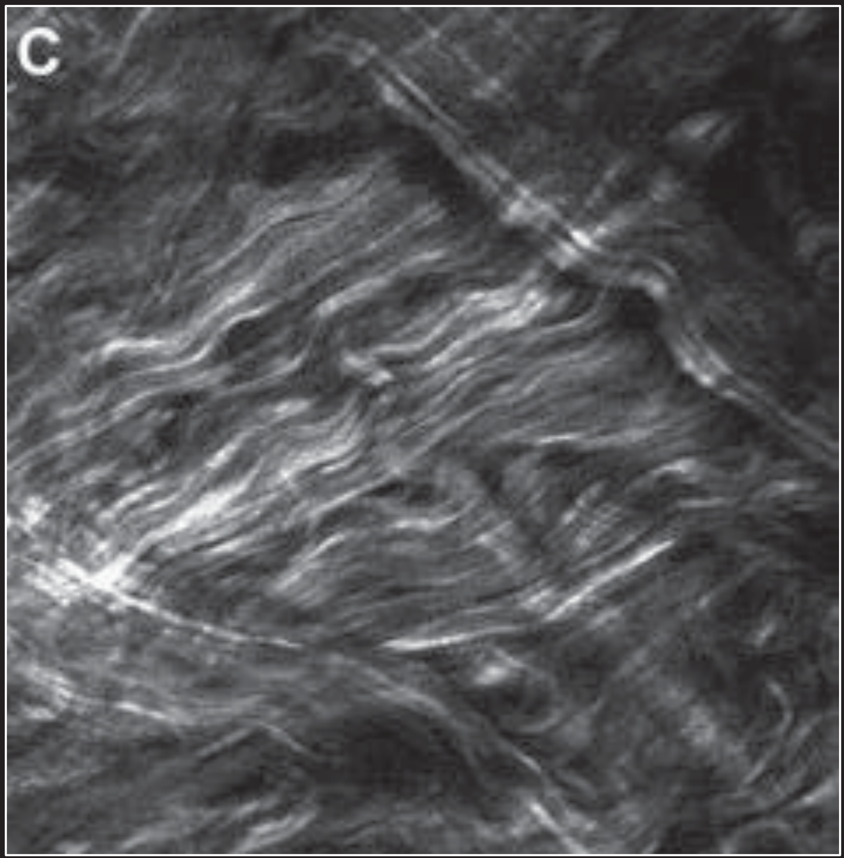


Geeraerts et al. Critical Care, 2008.

Collagen Structure



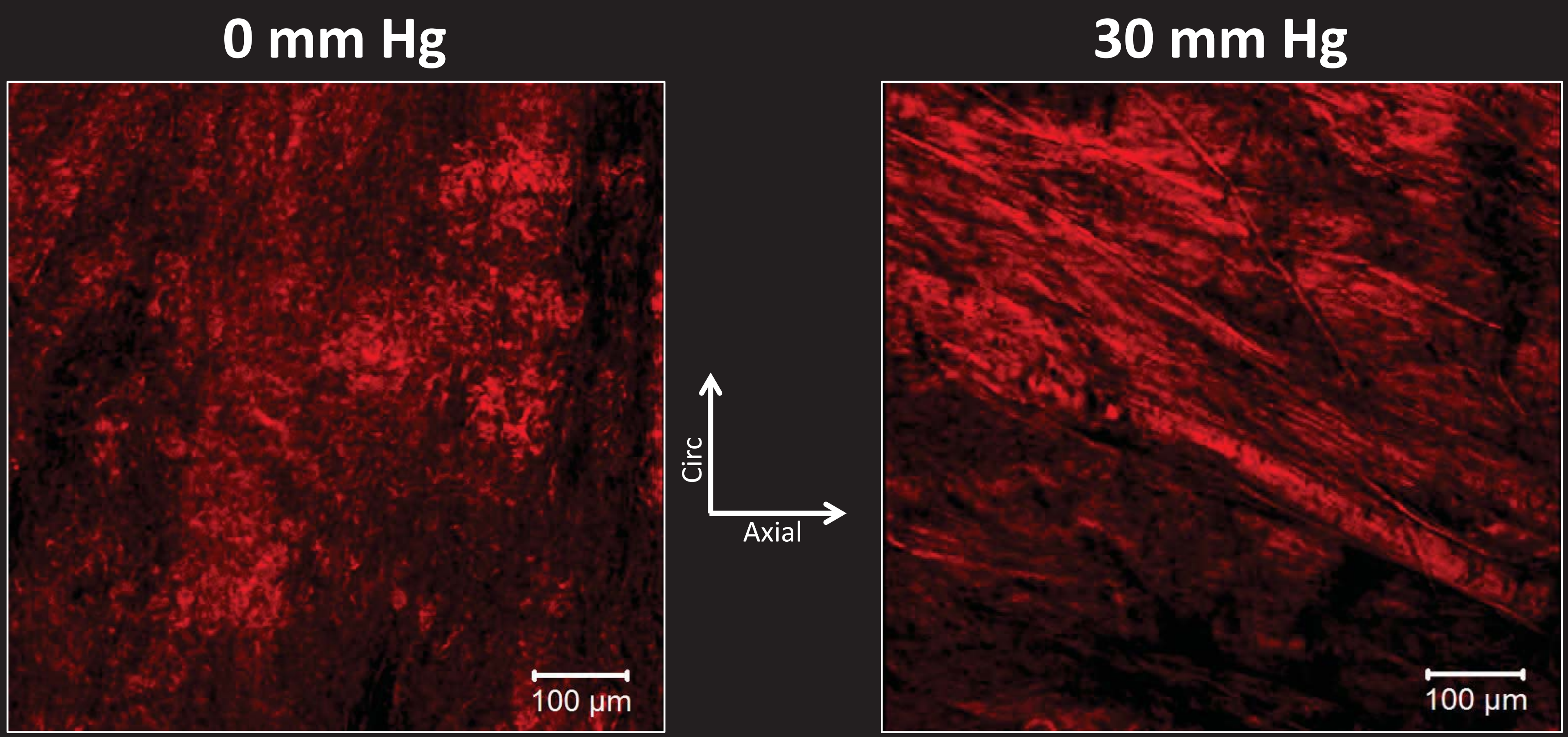
Post Mortem Porcine Optic
Nerve Sheath



Arterial Adventitia

Beal et al. Journal of Surgical Research, 2013.

Collagen Orientation Changes with Pressure



Experimental Summary

- Optic nerve sheath exhibits typical soft tissue behavior:
  - Preconditioning effect, with repeatable behavior after 4th pressure cycle
  - Nonlinear stiffening
  - Anisotropic collagen orientation

- Structure and behavior appears to be similar to the adventitia

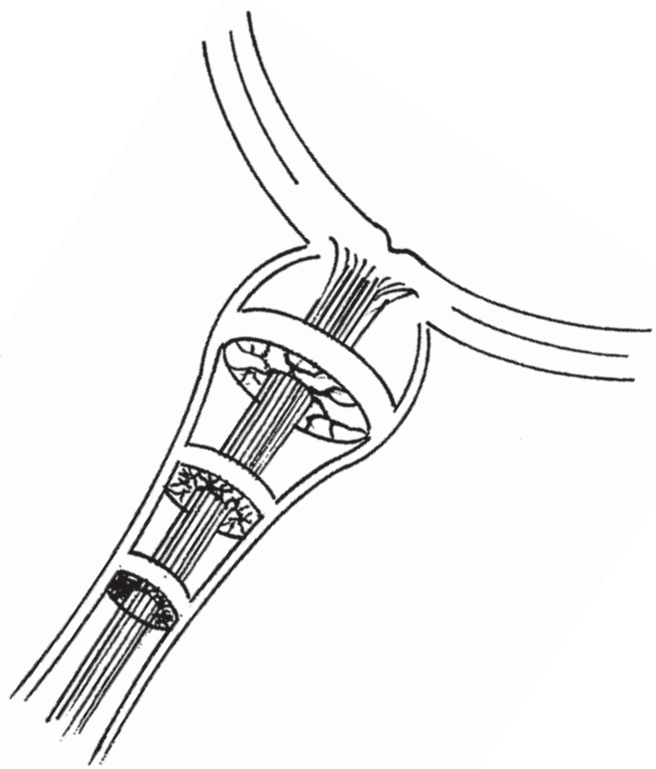
- High permeability suggests CSF drainage could play an important role in fluid transport in the optic nerve sheath

Limitations

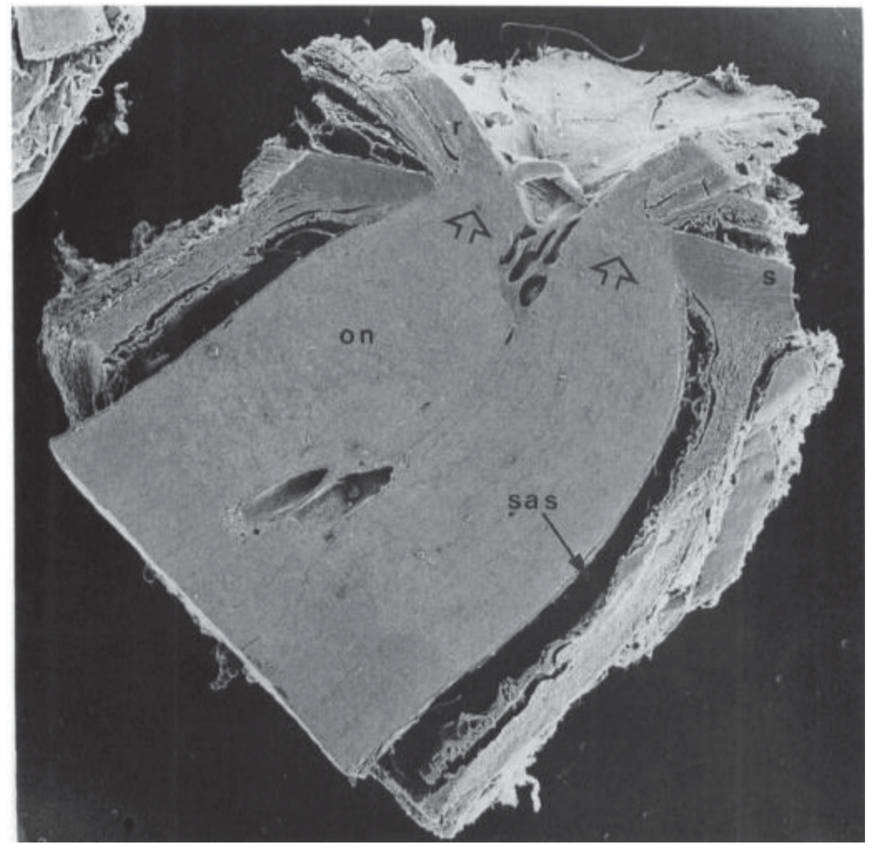
- Peeling back the meninges could cause structural damage
- Lack of availability of long human optic nerves
- Post mortem effects on permeability?

MODELING

Basic Modeled Geometry



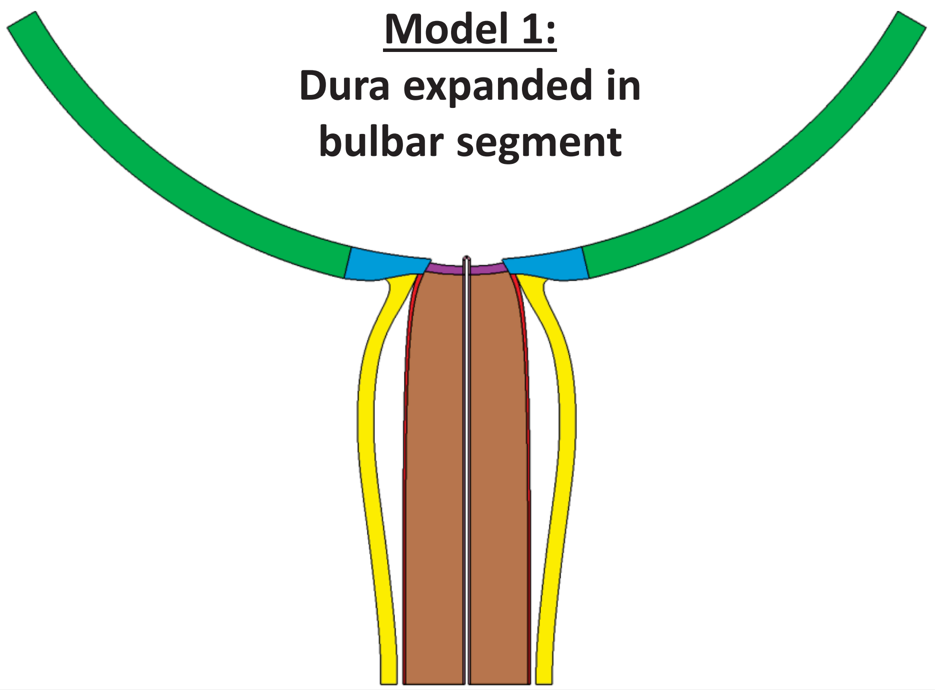
Hansen et al. Acta Ophthalmologica, 2011.

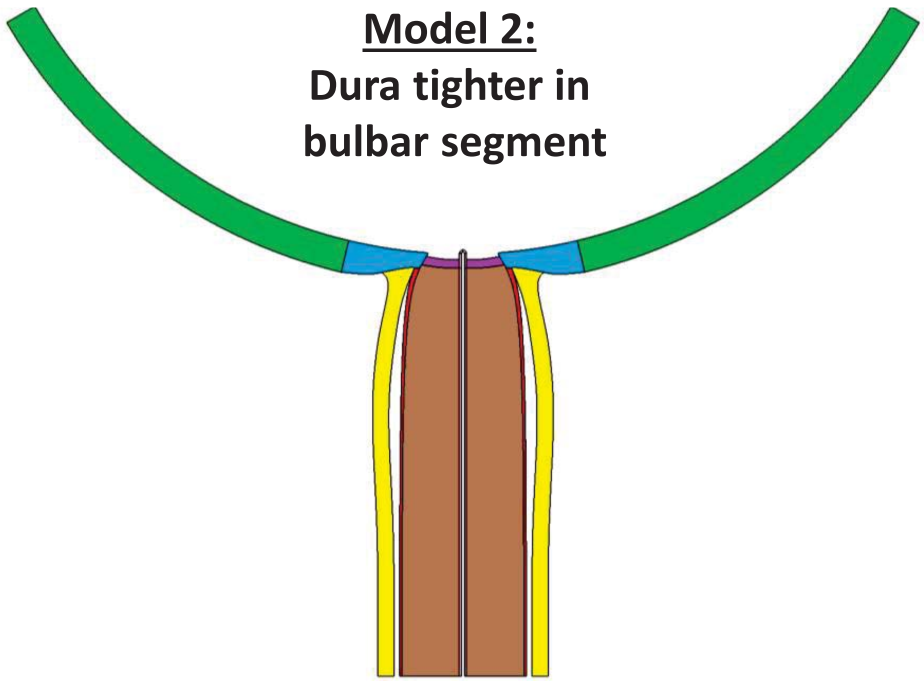


Adopted from Ekington et al. 1990

Basic Modeled Geometry

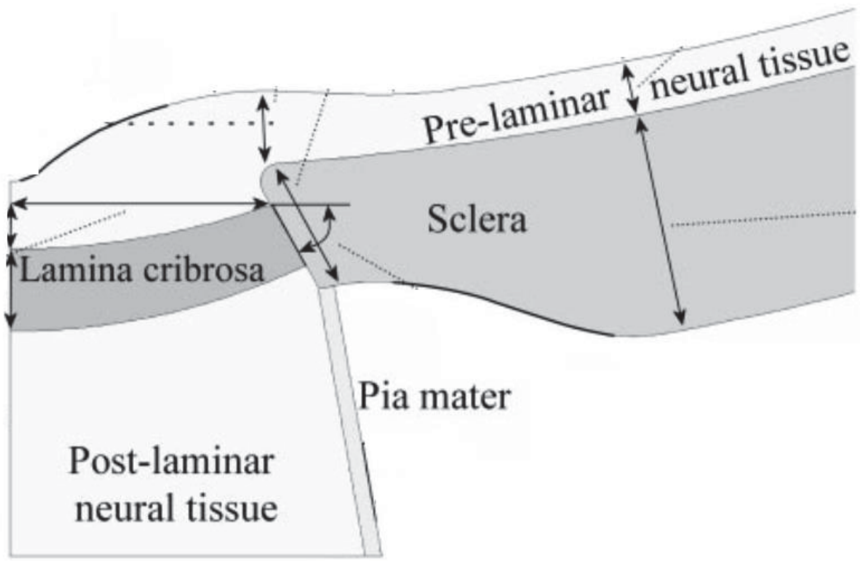
Two dura mater geometries considered



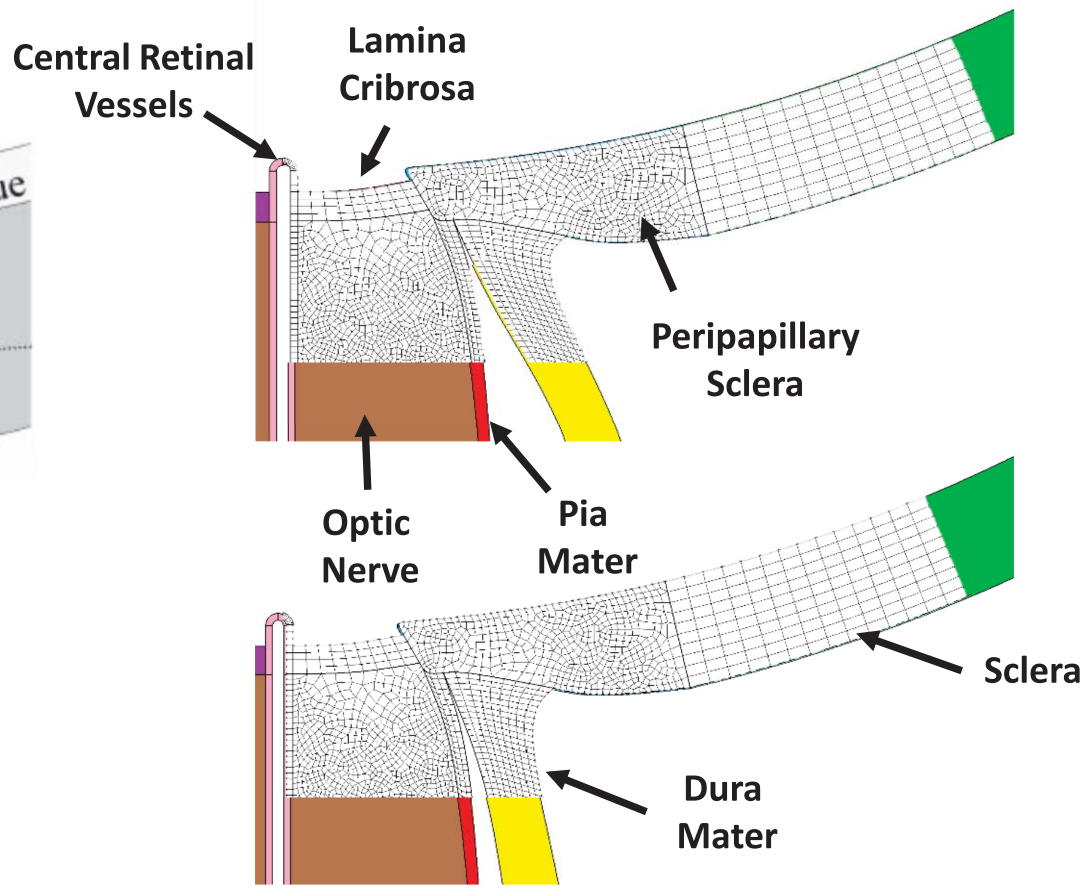


Optic Nerve Head (ONH) Geometry

- Based on models of Sigal et al., 2005

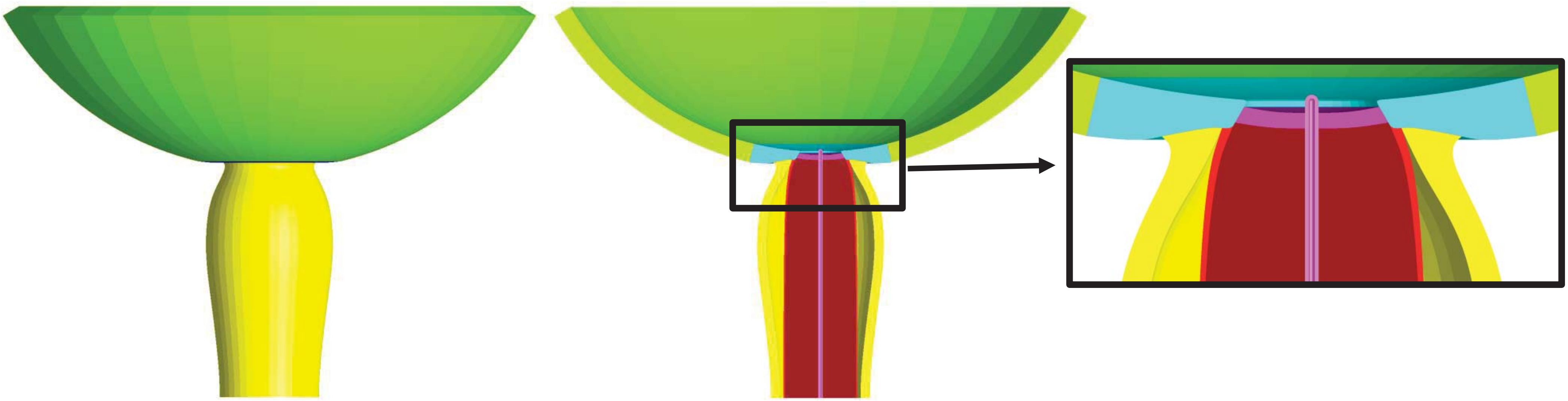


Sigal et al. 2005



Material parameters

- Linearly elastic
  - Sclera – 3.0 MPa
  - Peripapillary Sclera – 3.0 MPa
  - Lamina Cribrosa – 0.3 MPa
  - Pia Mater – 3.0 MPa
  - Dura Mater – 1.0 MPa
  - Retinal Vessel Wall – 0.3 MPa



Loading

1. Baseline (Standing or walking)

   IOP – 15 mmHg **ICP - 0 mmHg** RVP – 55 mmHg

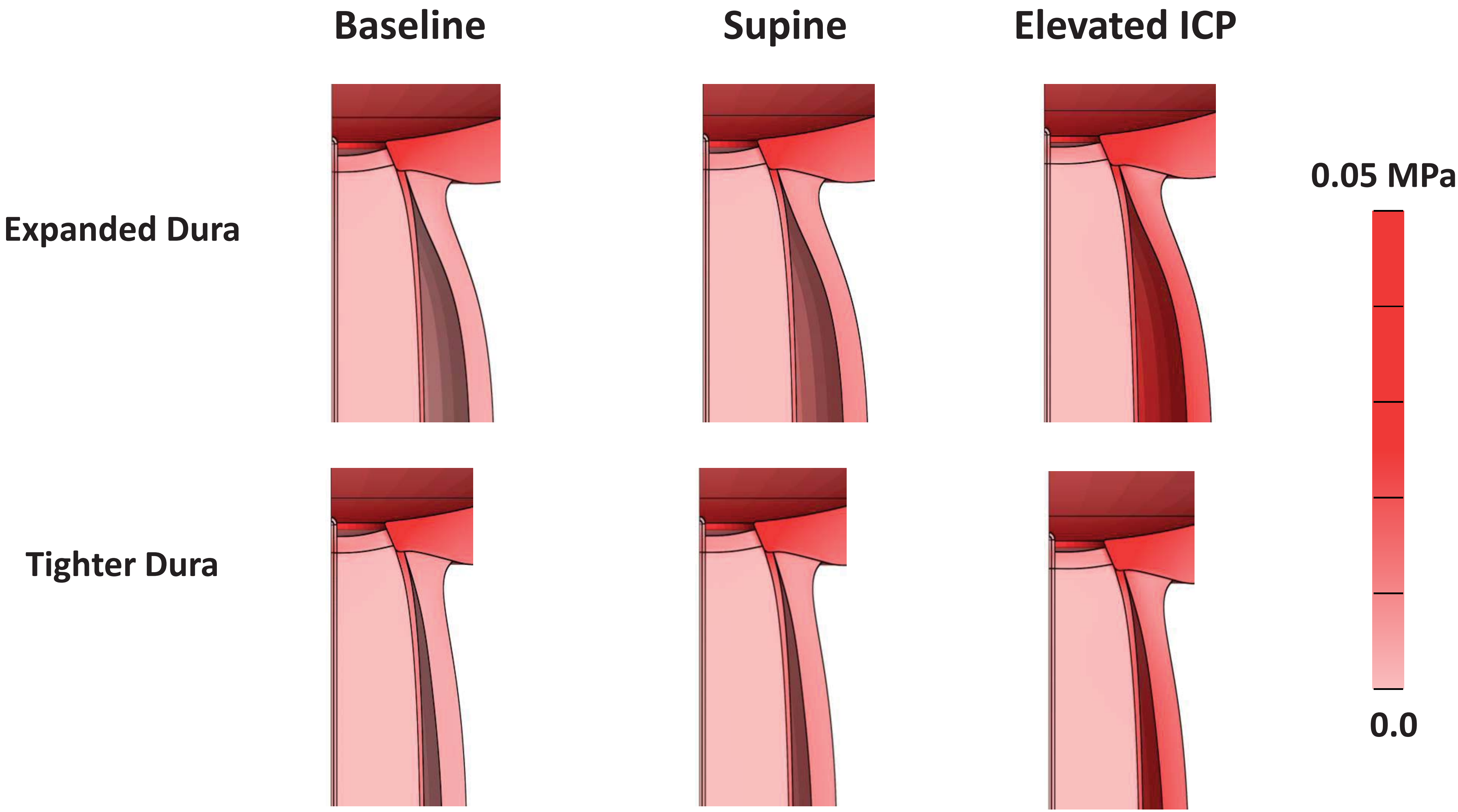
2. Supine

   IOP – 15 mmHg **ICP - 12 mmHg** RVP – 55 mmHg

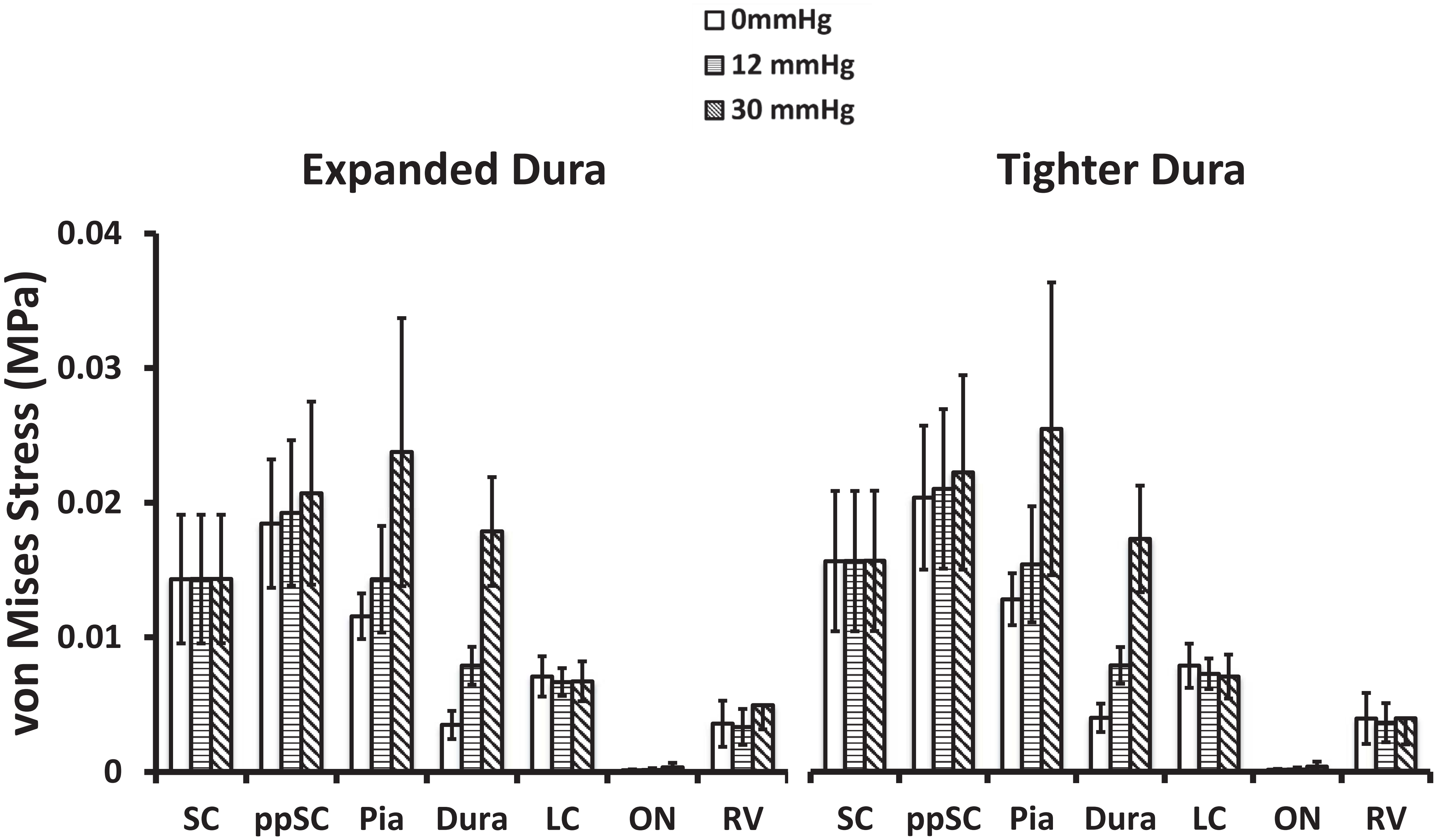
3. Elevated ICP

   IOP – 15 mmHg **ICP - 30 mmHg** RVP – 55 mmHg

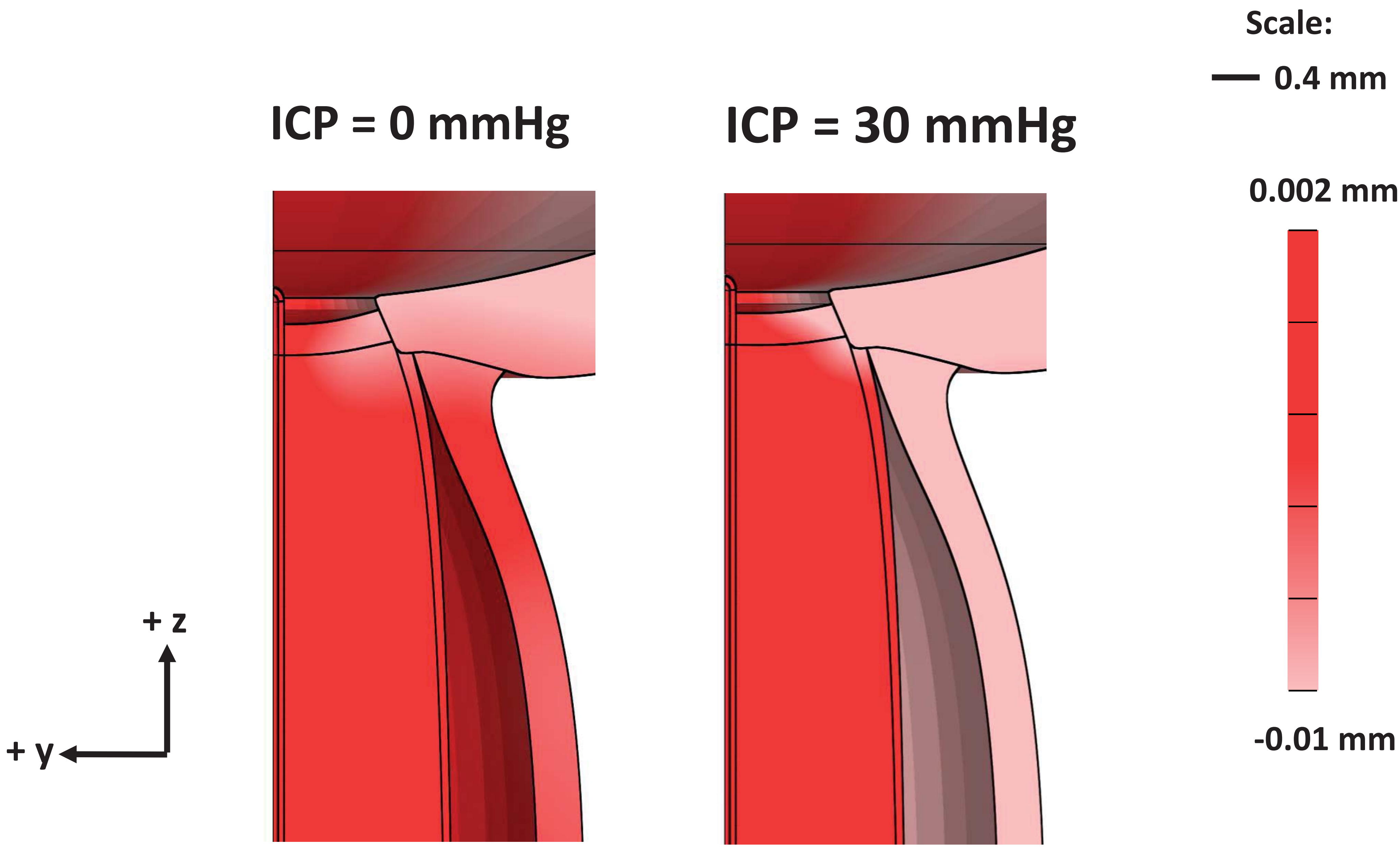
von Mises Stress



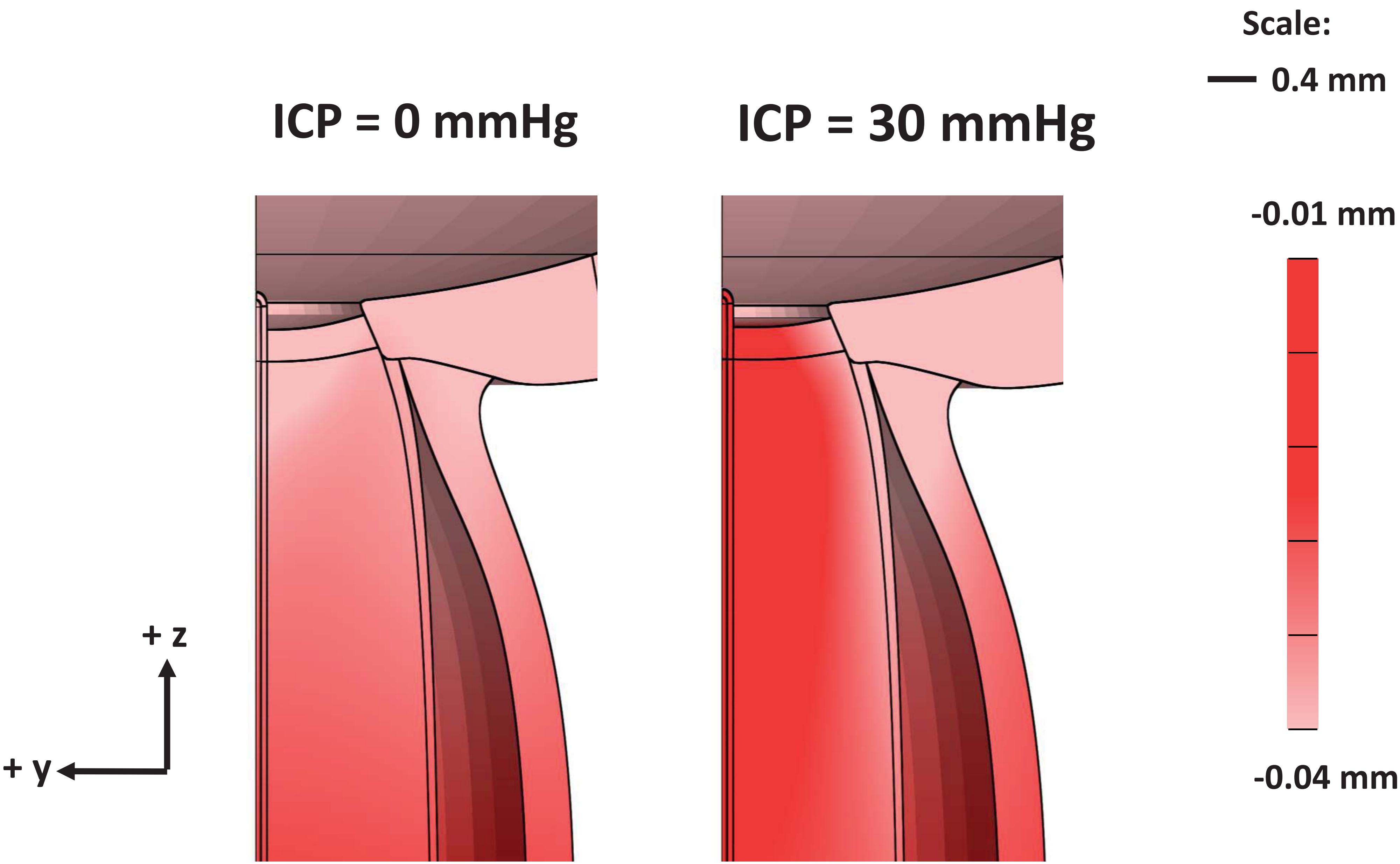
von Mises Stress Distributions



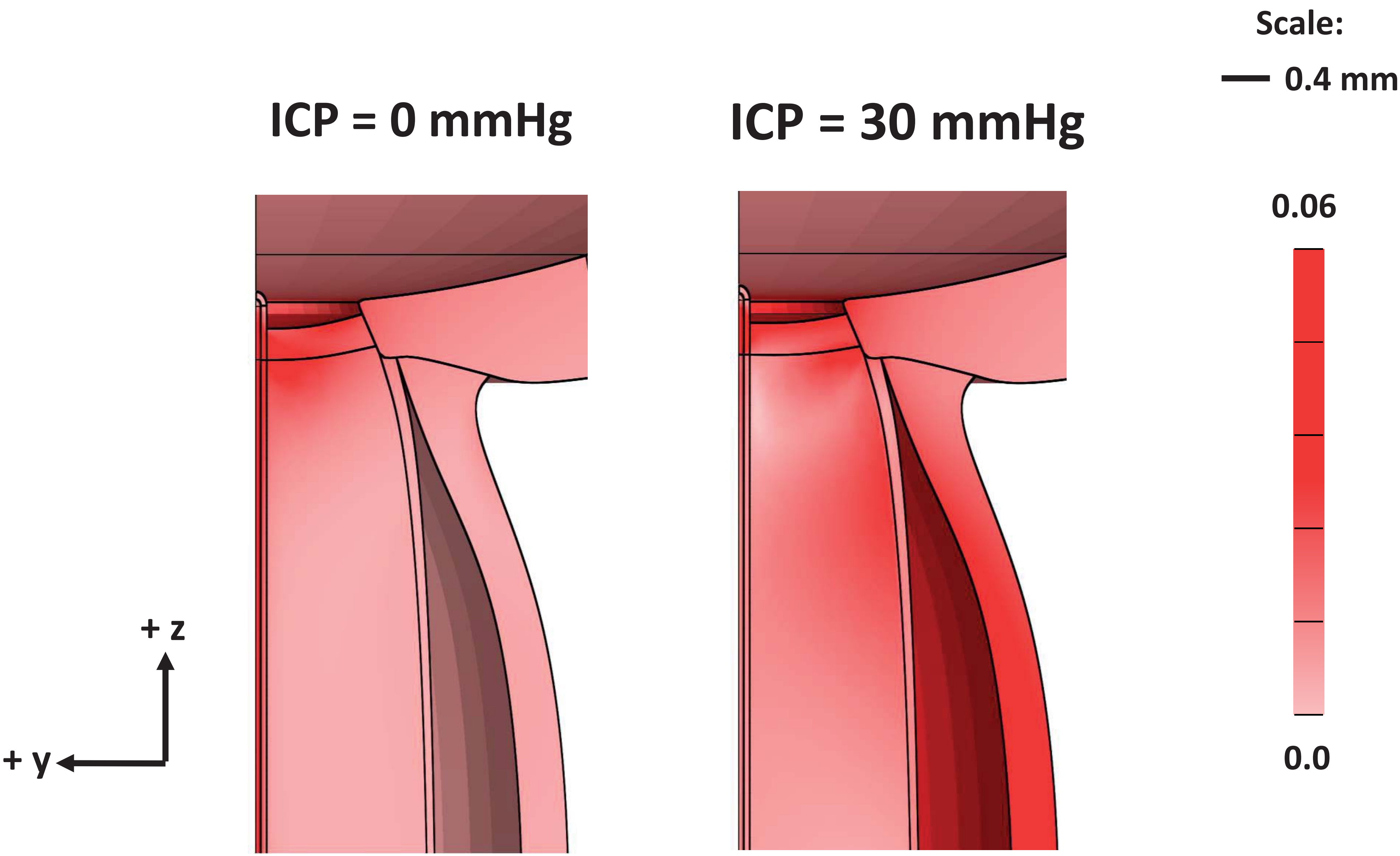
Y-displacement



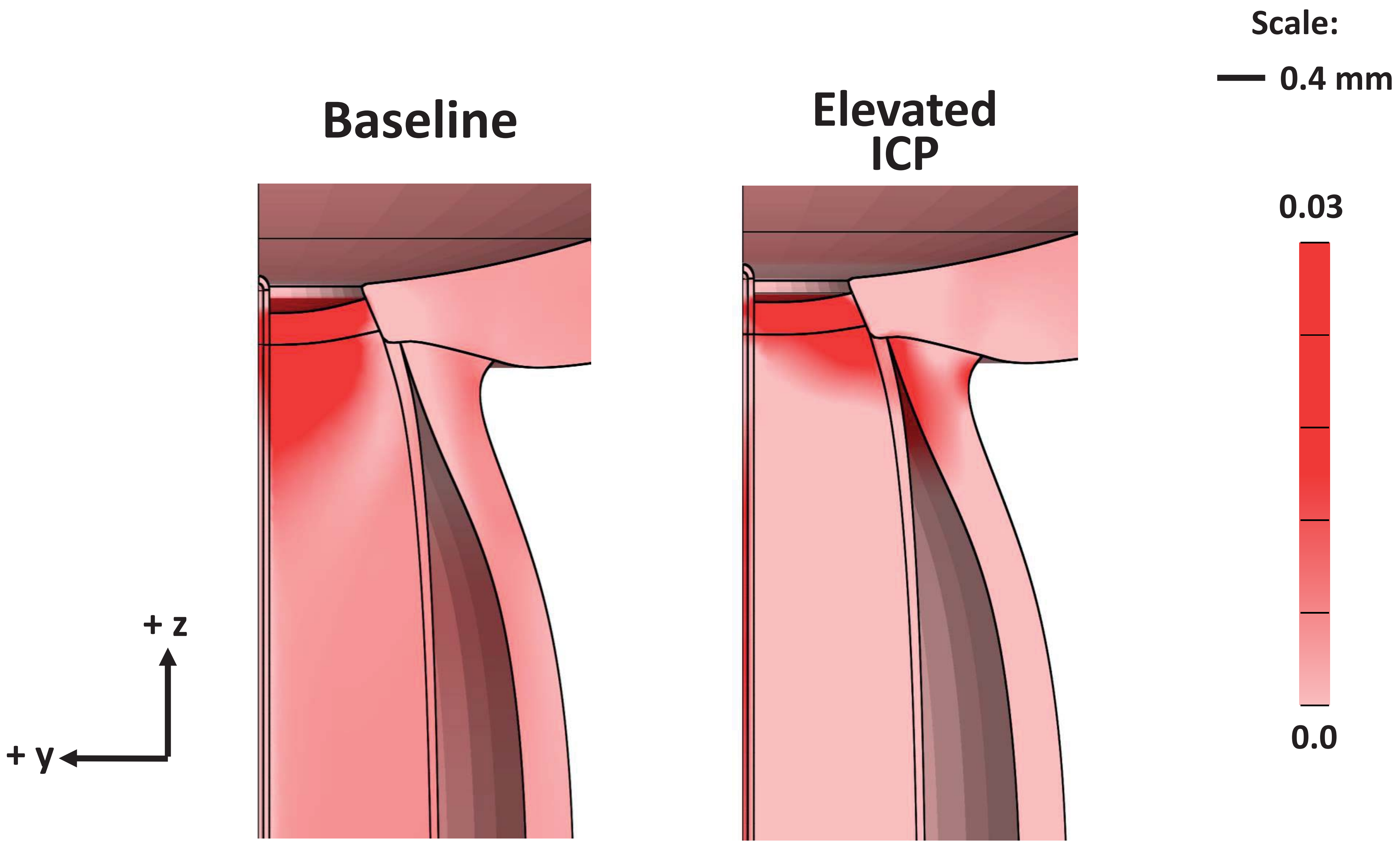
Z-displacement



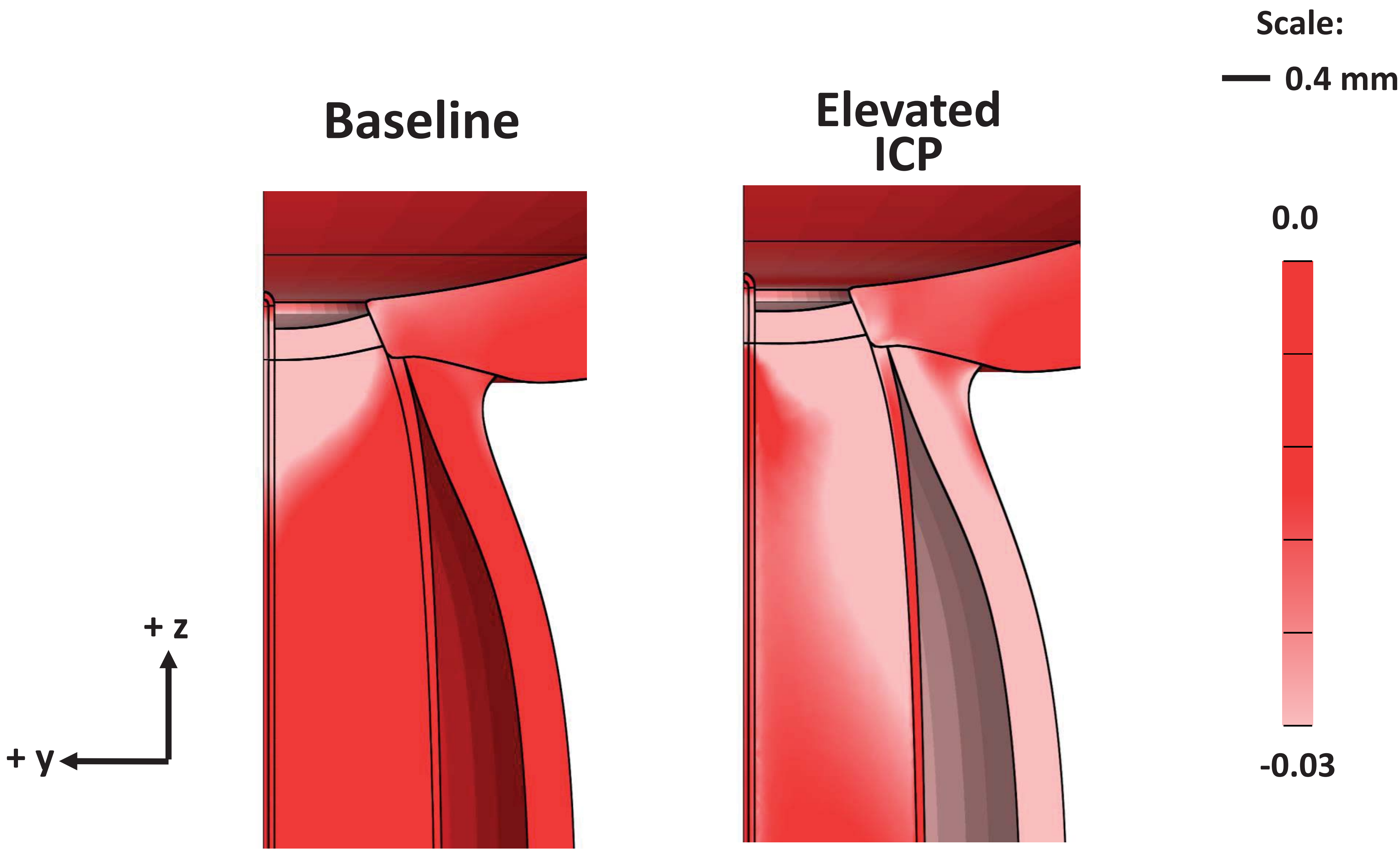
1st Principal Strain



2^{nd} Principal Strain

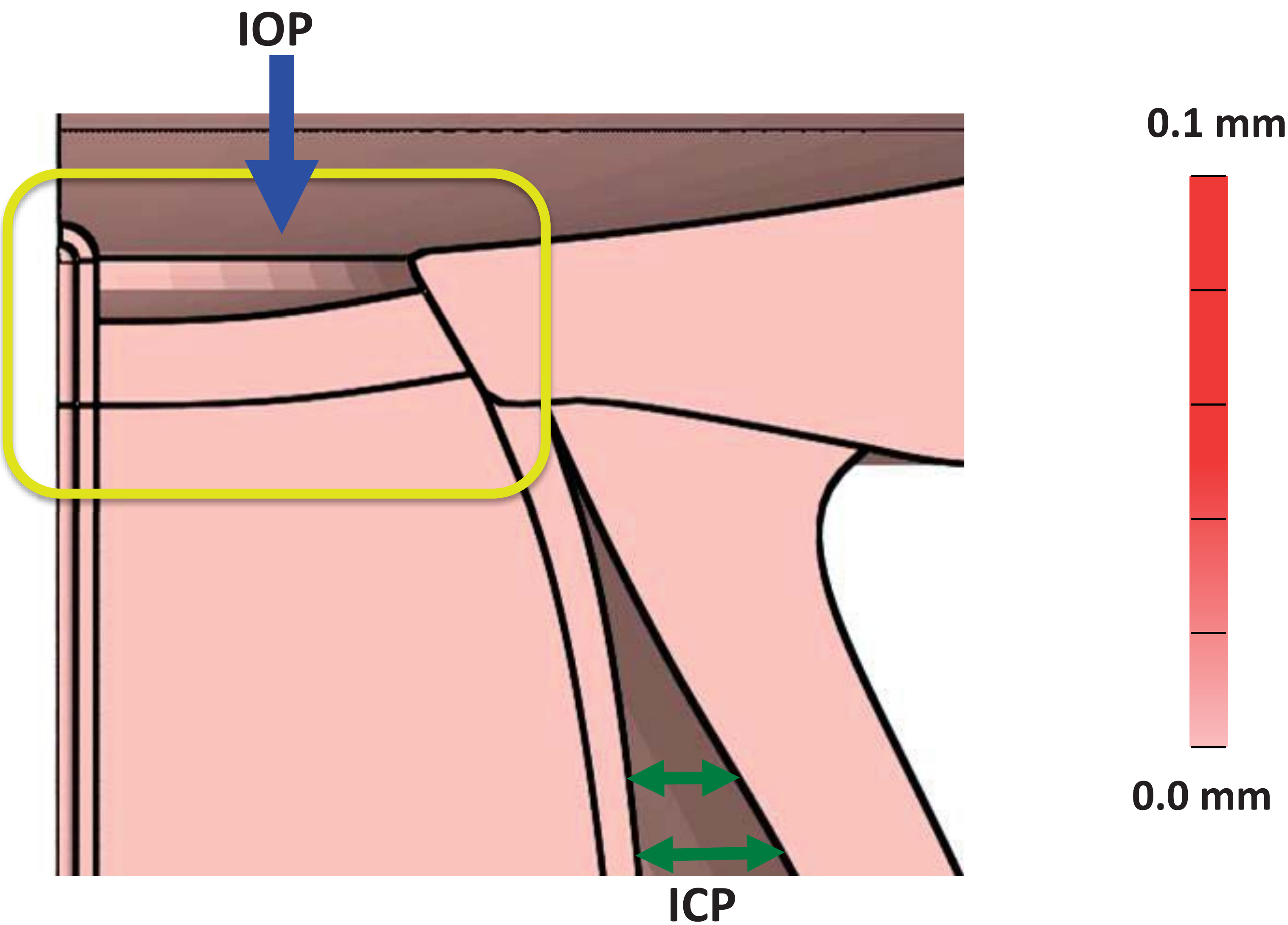


3^{rd} Principal Strain



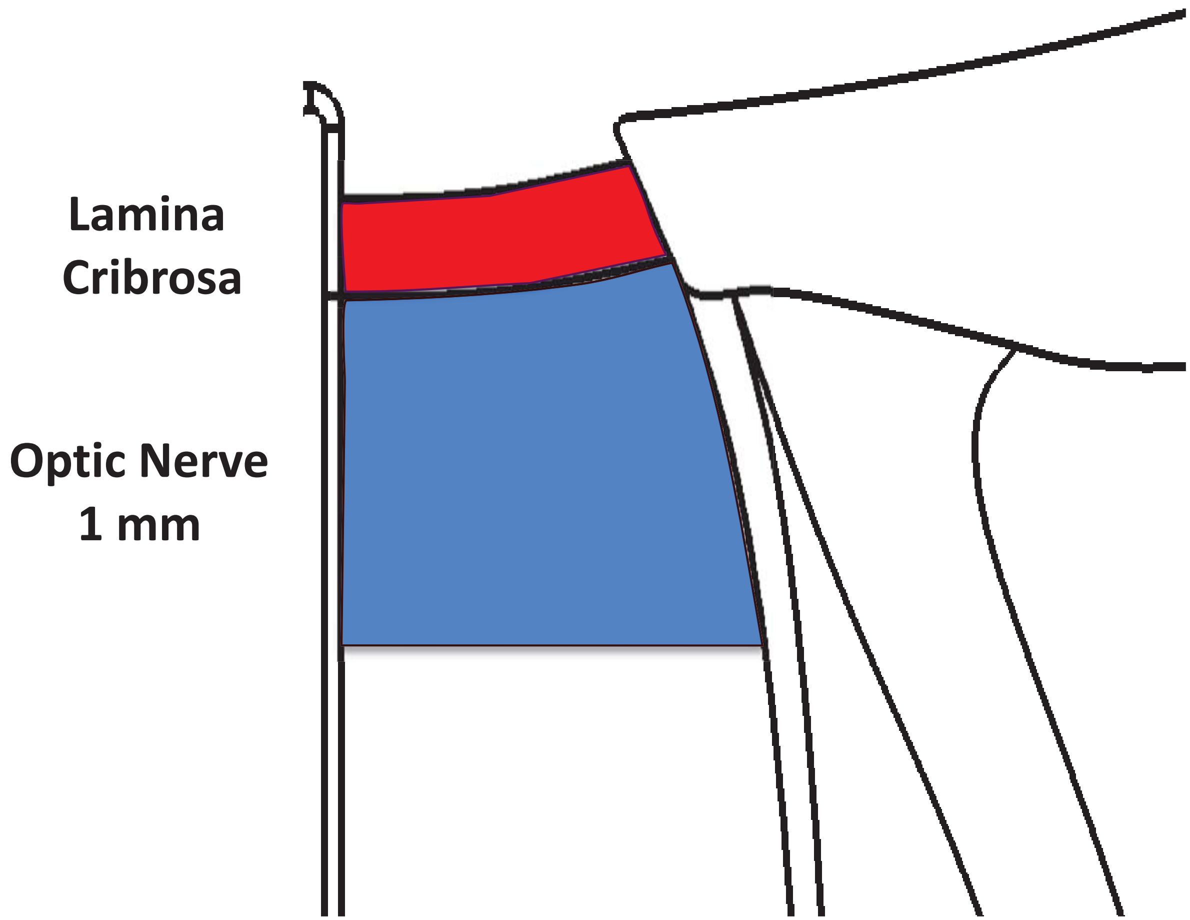
Displacements

Increase ICP: 0 to 30 mmHg

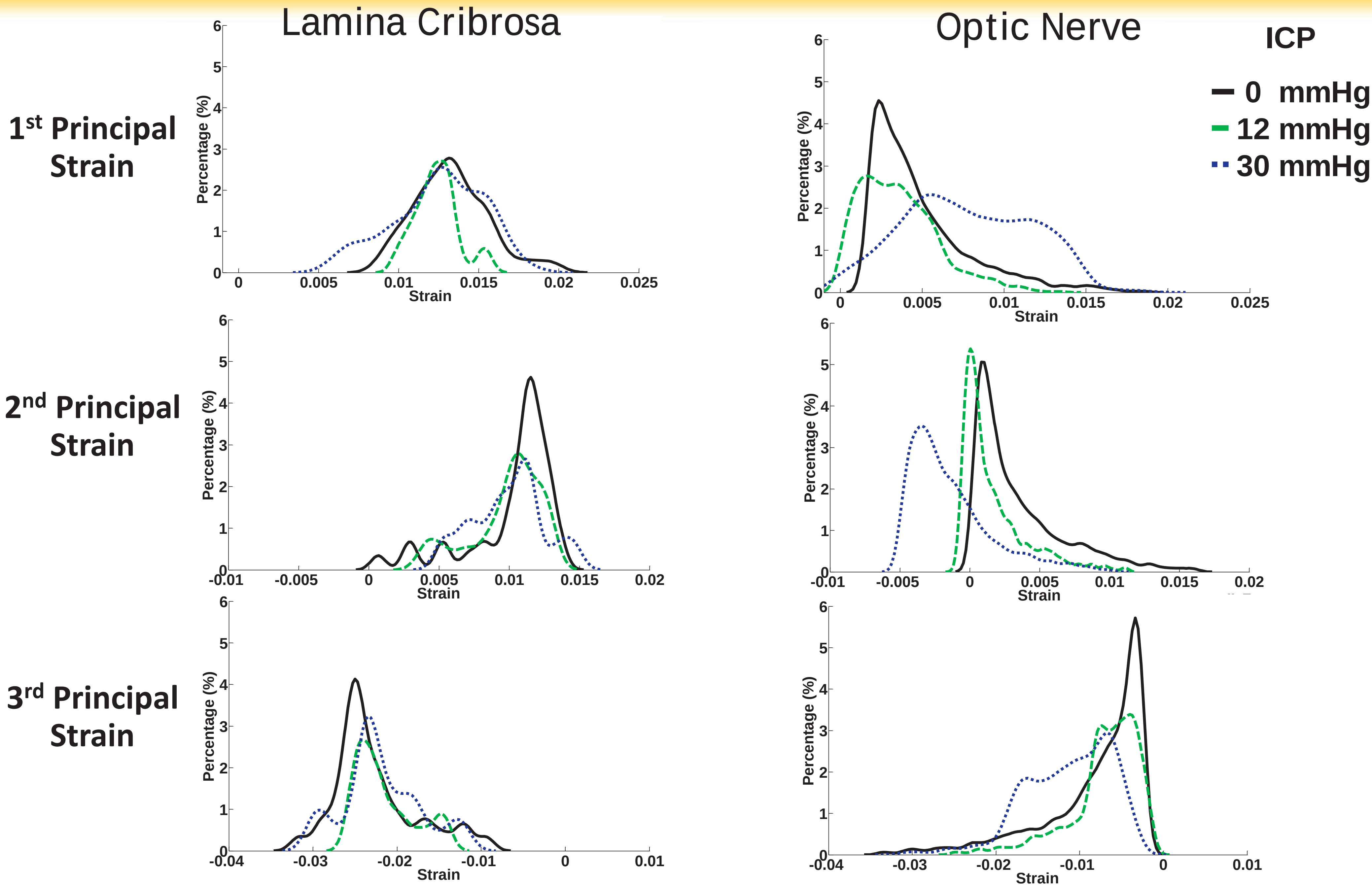


* Color scale is total displacement

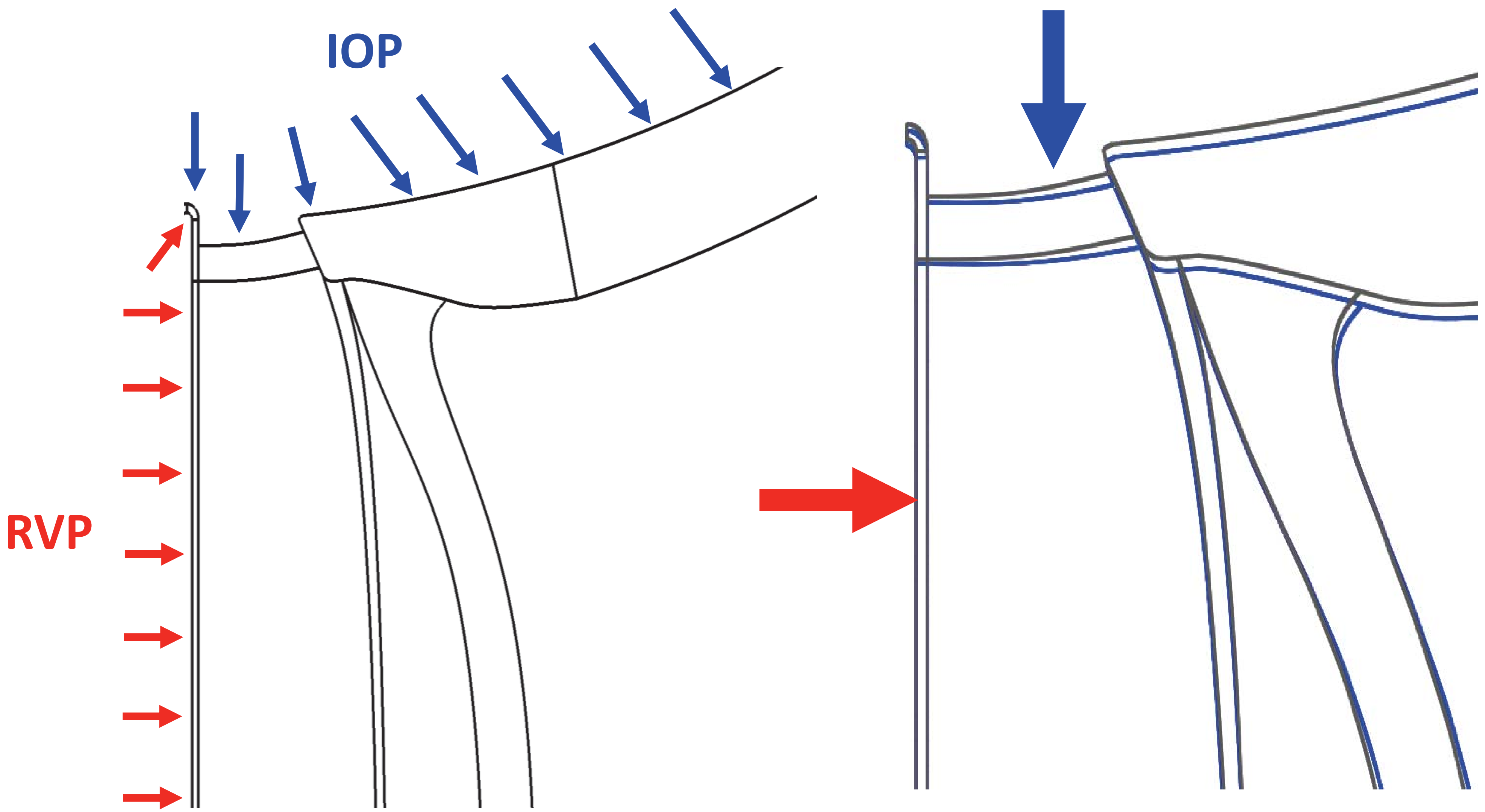
Regions of Interest



Principal Strain Distributions



Schematic Description



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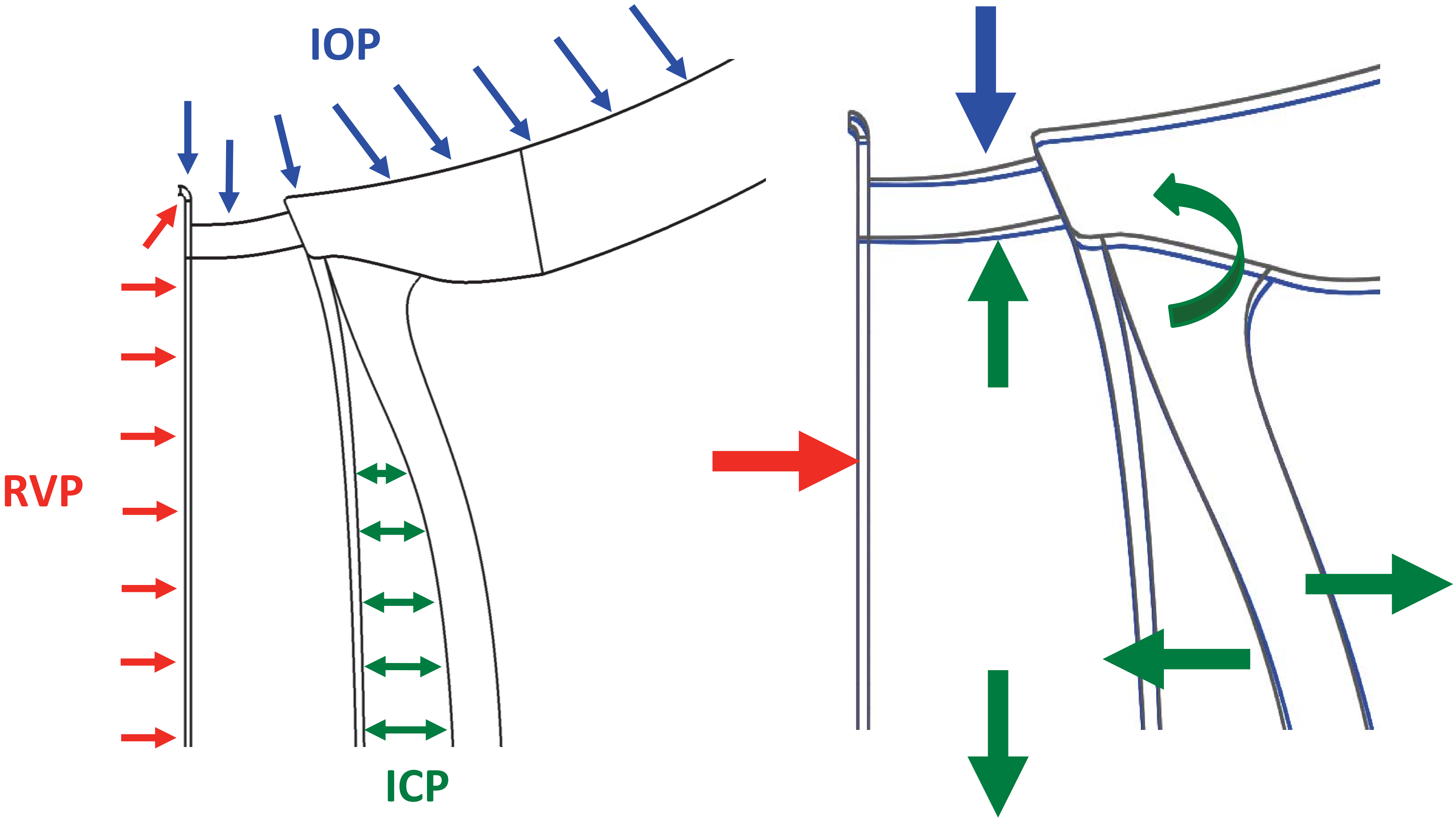
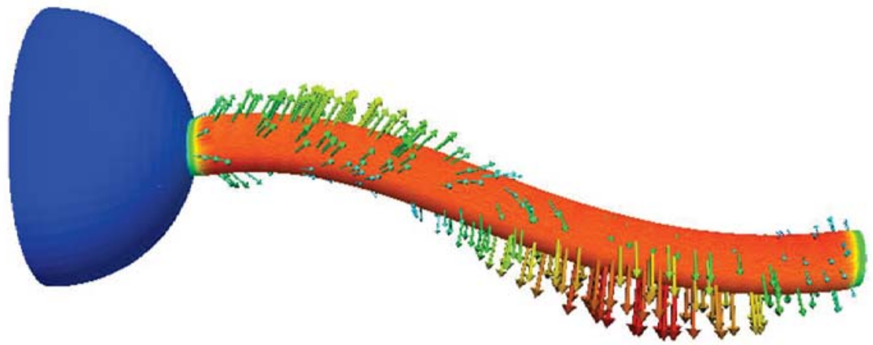


Future Directions

- Quantify collagen microstructural changes during mechanical loading
- Incorporate collagen microstructure into computational models of VIIP syndrome
- Study possible static instability in ONS



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